

Episodic Mass Loss from the Hydrogen-Deficient Central Star of the Planetary Nebula Longmore 4¹

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¹Based on observations with the 1.5-m telescope operated by the SMARTS Consortium at Cerro Tololo Interamerican Observatory.

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ABSTRACT

A spectacular transient mass-loss episode from the extremely hot, hydrogen-deficient central star of the planetary nebula (PN) Longmore 4 was discovered in 1992 by Werner et al. During that event, the star temporarily changed from its normal PG 1159 spectrum to that of an emission-line low-luminosity early-type Wolf-Rayet [WCE] star. After a few days, Lo 4 reverted to its normal, predominantly absorption-line PG 1159 type. To determine whether such events recur, and if so how often, I monitored the optical spectrum of Lo 4 from early 2003 to early 2012. Out of 81 spectra taken at random dates, four of them revealed mass-loss outbursts similar to that seen in 1992. This indicates that the episodes recur approximately every 100 days (if the recurrence rate has been approximately constant and the duration of a typical episode is ~ 5 days), and that the star is in a high-mass-loss state about 5% of the time. Since the enhanced stellar wind is hydrogen-deficient, it arises from the photosphere and is unlikely to be related to phenomena such as a binary or planetary companion or infalling dust. I speculate on plausible mechanisms for these unique outbursts, including the possibility that they are related to the non-radial GW Vir-type pulsations exhibited by Lo 4. The central star of the PN NGC 246 has stellar parameters similar to those of Lo 4, and it is also a GW Vir-type pulsator with similar pulsation periods. I obtained 167 spectra of NGC 246 between 2003 and 2011, but no mass ejections were found.

Subject headings: stars: mass loss — stars: individual (PG 1159–035, LV Vel, GW Vir) — stars: winds, outflows — planetary nebulae: individual (K 1-16, Lo 4, NGC 246)

1. Introduction

Longmore 4 (Lo 4; PN G274.3+09.1) is a low-surface-brightness planetary nebula (PN), discovered by Longmore (1977) during the ESO-SRC southern-hemisphere sky survey. Spectroscopic observations of its $V = 16.6$ central star by Méndez et al. (1985) led to a spectral classification as a PG 1159 star.

PG 1159-type objects (the name refers to the prototypical star PG 1159–035) are extremely hot, hydrogen-deficient planetary-nebula nuclei (PNNi) and white dwarfs, having spectra with a conspicuous C IV and He II absorption trough at 4659–4686 Å, and no features due to hydrogen (apart from a rare class of “hybrid PG 1159” stars showing traces of H). The high-excitation O VI 3811–3834 Å doublet is often seen in emission in the spectra of these stars, and if so they are sometimes referred to as having “O VI”-type spectra, or early WC types. Werner, Rauch, & Kruk (2007) found atmospheric parameters for the Lo 4 central star of $T_{\text{eff}} = 170,000$ K, $\log g = 6$. This result, based on the detection of Ne VIII absorption lines in *FUSE* FUV spectra, was a substantial upward revision in the temperature compared to an earlier analysis that had given $T_{\text{eff}} = 120,000$ K, $\log g = 5.5$ (Rauch & Werner 1997).

The spectrum of Lo 4 is quite similar to that of K 1-16, the first known pulsating PNN (Grauer & Bond 1984), and a member of the GW Vir class of non-radially pulsating white dwarfs (reviewed in recent years by Fontaine & Brassard 2008, Quirion 2009, and Althaus et al. 2010). This close similarity was borne out by the discovery of photometric pulsations in Lo 4 by Bond & Meakes (1990). Lo 4 was, at the time, only the second known pulsating PNN, having a strong periodicity near 31 min (1850 s), along with at least 8 other pulsation modes ranging from 831 to 2325 s. Based on its light variations, the central star has been given the variable-star designation LV Velorum, but in this paper I will refer to the star as Lo 4.

2. A Spectacular Mass-Loss Event in Lo 4

A remarkable transient mass-loss event that occurred in Lo 4 in 1992 was discovered serendipitously by Werner et al. (1992, 1993). For several days the spectrum changed from PG 1159 to a low-luminosity early carbon Wolf-Rayet, or [WCE], type of about [WC2-3]. During this event, the spectrum of Lo 4 had strong emission at the C IV complex near 4659 Å, at He II 4686 Å, and at O VI 5291 Å. Within a few days, the star reverted back to its usual PG 1159 spectrum, with the C IV and He II features once more in absorption. The mass-loss rate during this outburst was estimated at $\dot{M} \simeq 5 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ by Werner et al. (1993). As emphasized by Werner et al., this dramatic and rapid change in spectral properties was a unique phenomenon, never before seen in any hot post-AGB star.

3. Spectroscopic Monitoring of Lo 4

At the time of the 1992 mass-loss episode, only a few spectra had ever been taken of Lo 4. This suggested that the outbursts are likely not rare events, in Lo 4 itself, and possibly in other PG 1159-type PNNi.

In order to explore this possibility, I began a program of regular spectroscopic monitoring of Lo 4 in early 2003, and continued it until early 2012. I used the 1.5-m telescope operated by the SMARTS Consortium¹, located at Cerro Tololo Interamerican Observatory. The 1.5-m telescope was equipped with a spectrograph at the RC focus and a CCD camera. Data were obtained in queue-scheduling mode by Chilean observers. I used the 26/I grating setup, giving a wavelength coverage of 3650–5400 Å, with a resolution of 4.3 Å. Exposure times were 3×900 s, yielding a S/N per resolution element of ~ 30 –40

¹SMARTS is the Small & Moderate Aperture Research Telescope System;
<http://www.astro.yale.edu/smarts>

on good nights. The CCD images were bias-subtracted and flat-fielded, combined for cosmic-ray removal, and then the spectra were extracted and wavelength-calibrated, all using standard IRAF² routines.

Data were obtained at essentially randomly chosen dates. I have given progress reports at two conferences (Bond 2008, 2010); the monitoring has now been discontinued and I present the final results here. Between 2003 February and 2012 February, 81 usable spectra of Lo 4 were obtained. Table 1 lists the dates of the observations. Four new mass-loss events were detected during this interval. Table 2 summarizes the dates of these spectroscopic outbursts.

Fig. 1 illustrates, as an example, the mass-loss episode that occurred on 2008 November 30. The spectra have been normalized to a flat continuum, and a 3-point boxcar smoothing has been applied. The top spectrum, 19 days before the event, is noisy but shows the normal state of Lo 4. On November 30 the O VI doublet at 3811-3834 Å had strengthened over its normal value, and the O VI 5291 Å emission line was much stronger than usual. Most dramatic was the appearance in strong emission of the C IV+He II feature at 4659–4686 Å, which is normally seen in absorption. This spectrum is very similar to the outburst spectrum detected by Werner et al. in 1992. An observation two days later, obtained on 2008 December 2 (not included in Fig. 1 because poor observing conditions made it very noisy), showed that the C IV+He II emission was already gone. A better spectrum from December 4, shown at the bottom of Fig. 1, verifies the absence of C IV+He II emission, as well as the near-disappearance of the O VI 5291 Å emission line.

²IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

I created a high-S/N spectrum of Lo 4 in its low state by averaging the 58 best spectra obtained between 2003 and 2012. This spectrum is shown at the top of Fig. 2, with the most prominent features of He II, C IV, and O VI marked. The next four spectra in the figure show the appearance during the four detected “high” states of greatly enhanced mass loss. The time intervals between these episodes and the previous and following observations showing normal low-state spectra were as follows: (1) 2006 Jan. 16: spectra 53 days earlier and 15 days later were normal; (2) 2006 Nov. 30: 56 days earlier, 17 days later; (3) 2008 Nov. 30: 19 days earlier, 2 days later; (4) 2011 Oct. 30: 164 days earlier, 21 days later. Thus, although the constraints are not tight, the events are likely of relatively short duration, no more than a few to several days, in agreement with the findings reported by Werner et al. (1992).

4. Observations of the Central Star of NGC 246

The nucleus of the PN NGC 246 is another PG 1159-type star, considerably brighter than Lo 4 (Bond & Ciardullo 1999 measured $V = 11.8$). Its parameters are similar within the errors to those of Lo 4; in the same paper in which they discussed *FUSE* observations of Lo 4, Werner et al. (2007) reported $T_{\text{eff}} = 150,000$ K, $\log g = 5.7$ for NGC 246. A further indication of the similarity of the two stars arises from the detection of GW Vir-type non-radial pulsations in NGC 246 (Ciardullo & Bond 1996; González Pérez, Solheim, & Kamben 2006), with periods of ~ 24 –31 min.

Does NGC 246 also have occasional episodes of enhanced mass loss? To explore this possibility, I obtained spectra with the SMARTS 1.5-m telescope for this star on 167 occasions, between 2003 June and 2011 July. In addition to the 26/I grating setup described above, the brightness of NGC 246 made it possible to use two higher-resolution setups: 56/II (4017–4938 Å, 2.2 Å resolution) and 47/IIb (4070–4744 Å, 1.6 Å resolution). Typical

exposure times were 3×240 s for 26/I and 3×300 s for 56/II and 47/IIb. In spite of the similar spectra, stellar parameters, and pulsational properties of the two stars, NGC 246 never showed mass-loss events like those of Lo 4 during the observations between 2003 and 2011. I will provide the observation dates to any interested readers.

I created a high-S/N spectrum for NGC 246 by averaging 21 excellent spectra. Fig. 3 compares this spectrum with the average low-state spectrum of Lo 4, and illustrates the similarity. However, the O VI emission features are noticeably weaker in NGC 246.

5. Constraints and Speculations

I detected four mass-loss episodes during 81 observations of Lo 4. Following the precepts used by Zwicky (1938) to determine the average rate of supernova explosions per galaxy, I can estimate the typical time between outbursts of Lo 4 (on the assumption that the recurrence rate has been approximately constant over the observing interval). Using Zwicky’s terminology, the “control value” of a single observation is the length of time during which an outburst would have been detectable (i.e., the duration of a typical mass-loss episode). Based on Werner et al. (1992) as well as my own results, the control value for Lo 4 is about $\tau \simeq 5$ days. Thus the total control value of the 81 observations is $81 \tau = 405(\tau/5)$ days (neglecting the small number of observations separated by less than τ days). Since 4 outbursts were detected, the mean rate of mass-loss events in Lo 4 is found to be about one every $101 (\tau/5)$ days (with a statistical uncertainty of about $\pm 50\%$ since only 4 events were detected). Moreover, we can estimate that the mean fraction of the total elapsed time during which Lo 4 was in outburst is about $\tau/[101 (\tau/5)] \simeq 5\%$, independent of the outburst duration as long as it is short compared to the typical spacing of the observations.

At present there seems to be no entirely satisfactory explanation for these transient mass-loss episodes in Lo 4. One constraint is that the temporary stellar wind is *hydrogen-deficient* and *helium-rich*, and thus must arise from photospheric material. This shows that the outbursts are unlikely to be related to accretion events involving a companion star, debris disk, infalling planet, or other exotic external cause. No 24 μm dust excess in Lo 4 was found in a *Spitzer* survey by Chu et al. (2011). The short durations of the episodes indicate that they are not driven on an evolutionary timescale.

Lo 4 lies in the HR diagram for hot post-AGB remnants near the boundary between emission-line [WCE] and predominantly absorption-line PG 1159 objects (e.g., Fig. 1 of Werner 2001). The general picture (cf. Koesterke & Werner 1998; Werner 2001; Koesterke 2001; Liebert 2008, Fig. 1) is that, as such stars evolve to lower luminosity, the strong radiatively driven winds of [WCE] objects gradually diminish, weakening the emission-line spectrum and transitioning the star to a PG 1159 spectral type. This suggests that, for a PG 1159 star just finishing this slow transition, it might take only a small perturbation to move it back into the [WCE] stage. A possible speculation is that occasionally many pulsation modes may be in phase, giving a temporarily large surface-temperature amplitude, which might trigger the outbursts. If so, we might expect the outbursts to occur periodically, at the beat period between the pulsation modes. However, I could find no obvious period that would predict the outburst dates listed in Table 1 without also predicting outbursts that were not seen to occur.

If we adopt the outburst mass-loss rate of $5 \times 10^{-8} M_{\odot} \text{yr}^{-1}$ given above, and if the star is in outburst $\sim 5\%$ of the time, the integrated mass-loss rate from Lo 4 due to its outbursts is $\sim 2.5 \times 10^{-9} M_{\odot} \text{yr}^{-1}$. There has not to my knowledge been a published estimate of the mass-loss rate for Lo 4 in its normal low state. However, a rough comparison is provided by the estimates for the similar K 1-16 and NGC 246 of $\sim 10^{-8}$ and $10^{-7} M_{\odot} \text{yr}^{-1}$, respectively

(Koesterke & Werner 1998). Thus the outbursts of Lo 4 appear to have relatively little additional effect on the evolution of the star.

We are left with a curious astrophysical puzzle: what is the origin of these episodic events in Lo 4? It would be useful to monitor the spectra of other PNNi lying near the [WCE]–PG 1159 transition. A stringent test of the hypothesis that in-phase pulsations produce the Lo 4 outbursts would be to search for the onset of an enhanced pulsation amplitude in the light curve and verify that a spectroscopic event is then triggered; however, since we cannot predict these outbursts in advance, such a program would be very costly in telescope time.

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Facilities: SMARTS 1.5-m telescope

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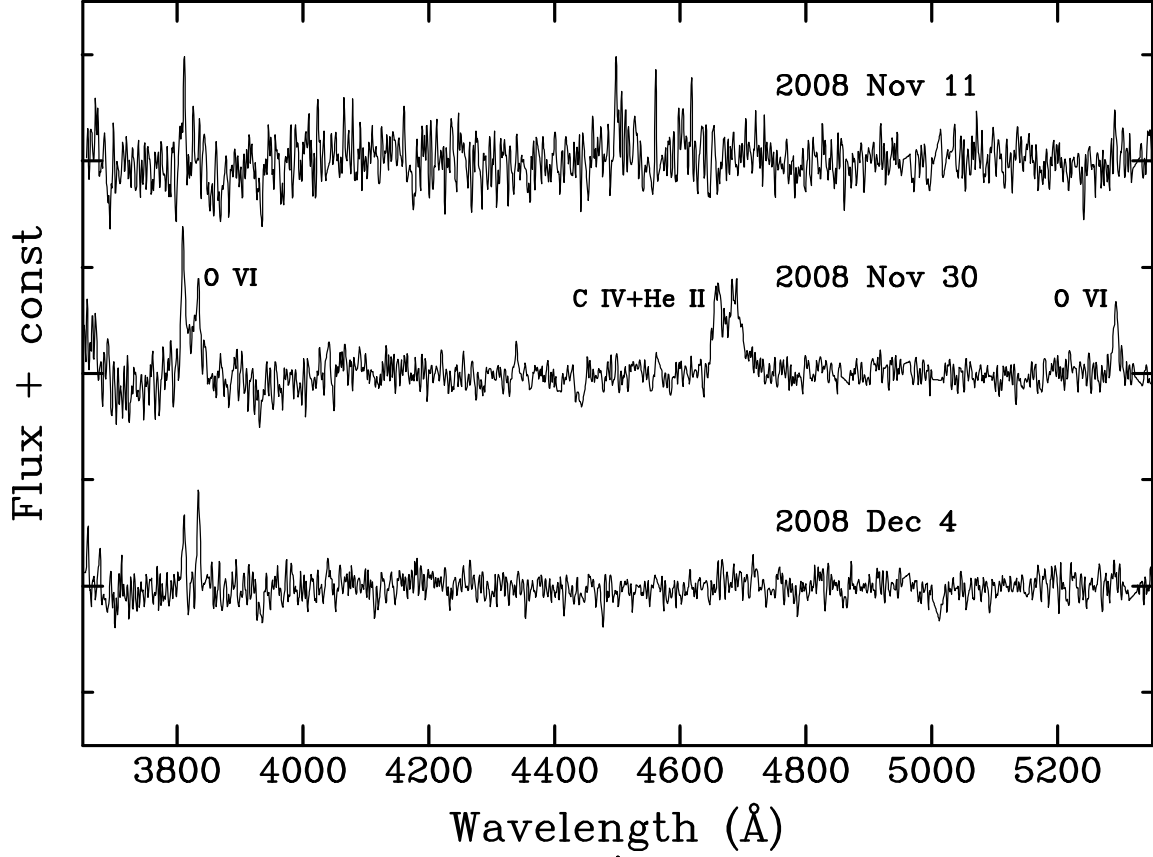


Fig. 1.— *Top*: SMARTS 1.5-m spectrum of Lo 4 on 2008 Nov 11; although noisy, it shows the star in its normal quiescent state. *Middle*: spectrum on 2008 Nov 30, showing that a mass-loss episode is underway. The C IV+He II feature is now strongly in emission, and the emission at the O VI lines is also stronger than in the normal state. *Bottom*: spectrum on 2008 Dec 4. Lo 4 is back to its normal state. All spectra have been normalized to a flat continuum, and tick marks on the y -axis are spaced at 0.5 of the continuum level.

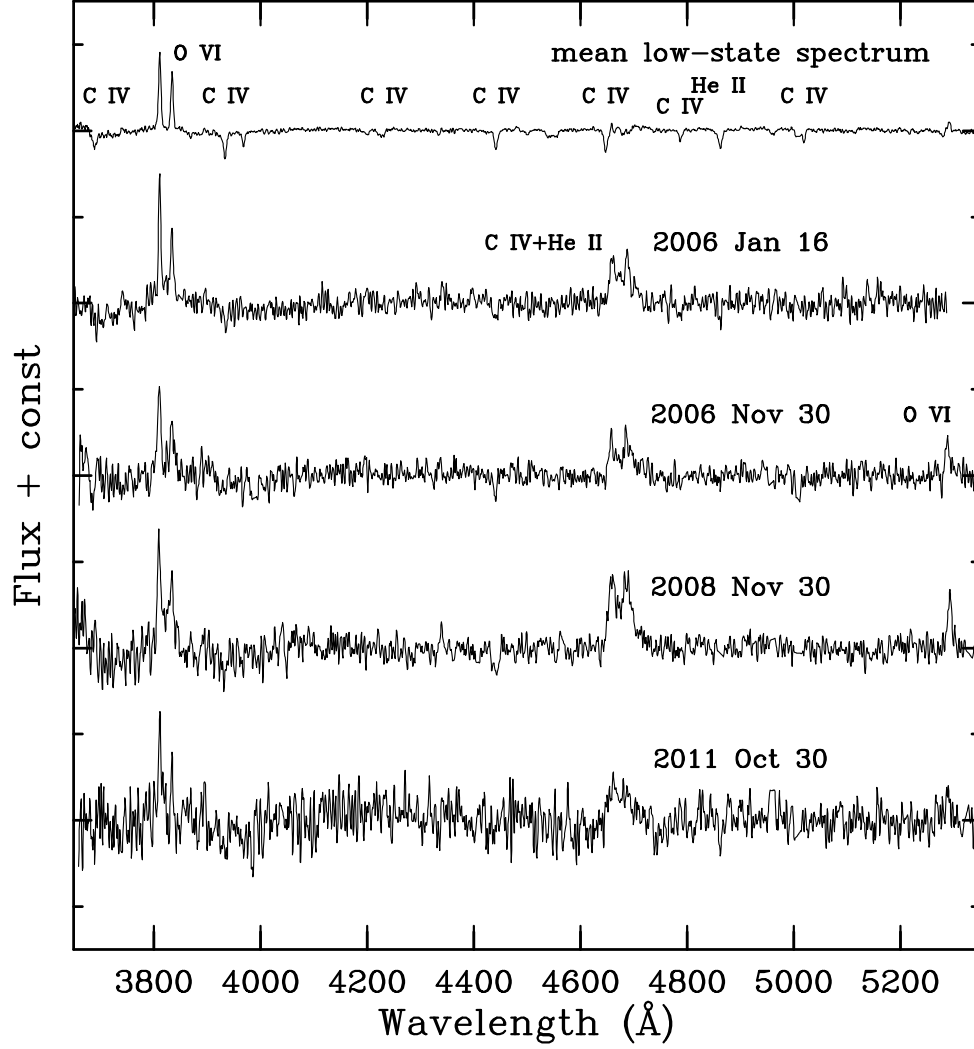


Fig. 2.— *Top*: high-S/N average spectrum of Lo 4 in its normal low state. Prominent absorption lines of He II and C IV are labelled, along with the emission doublet of O VI at 3811–3834 Å. *Bottom*: spectra of Lo 4 showing the four mass-loss events detected during the 2003–2012 interval. Tick marks on the y -axis are spaced at 0.5 of the continuum level.

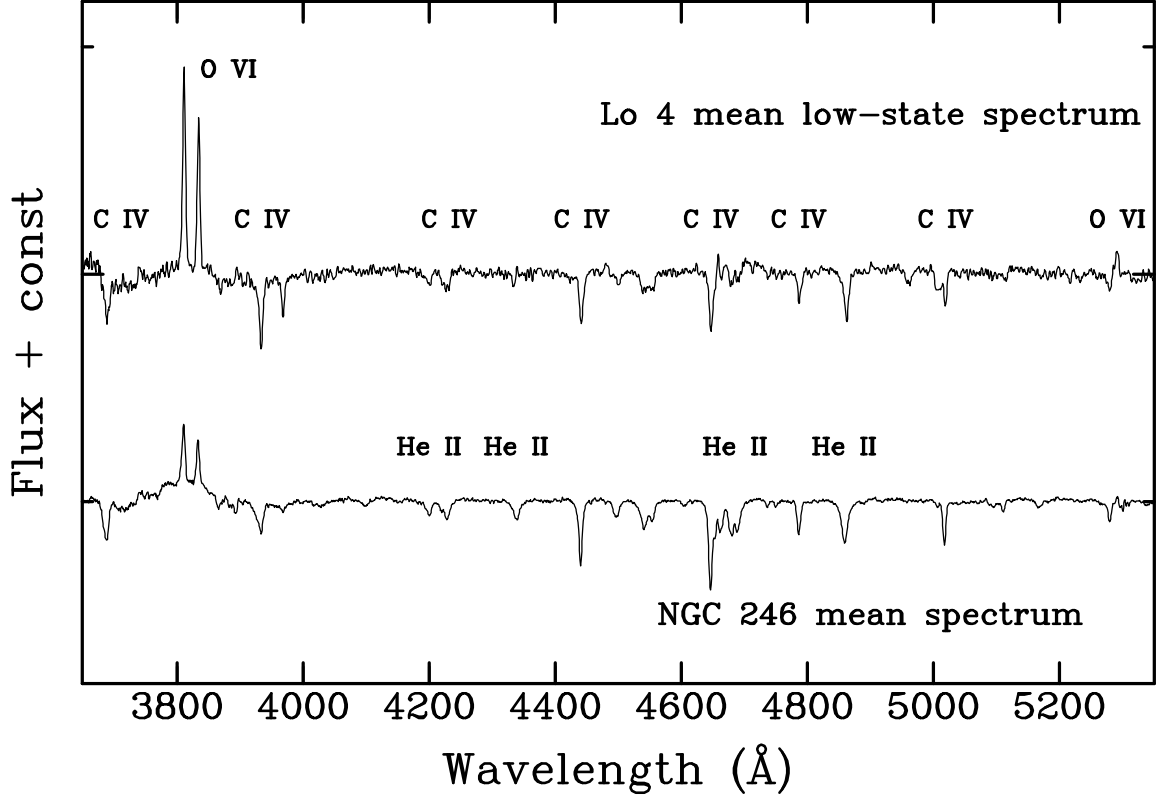


Fig. 3.— *Top*: high-S/N spectrum of Lo 4 in its normal state from Fig. 2. *Bottom*: high-S/N spectrum of the central star of NGC 246. Tick marks on the y -axis are spaced at 0.5 of the continuum level.

Table 1. Dates of Spectroscopic Observations of Lo 4

Civil Date	Civil Date	Civil Date	Civil Date
2003-02-19	2006-05-08	2008-05-15	2010-10-06
2003-03-12	2006-06-03	2008-06-21	2010-11-10
2003-04-04	2006-10-04	2008-07-03	2010-11-26
2003-04-19	2006-11-29	2008-07-13	2010-12-29
2003-05-07	2006-12-16	2008-10-23	2011-01-10
2003-06-11	2006-12-18	2008-11-10	2011-01-27
2003-06-25	2006-12-20	2008-11-29	2011-02-12
2004-01-11	2006-12-22	2008-12-01	2011-03-02
2004-01-31	2007-01-17	2008-12-03	2011-03-16
2004-04-16	2007-02-08	2008-12-07	2011-04-16
2004-11-05	2007-02-11	2008-12-28	2011-05-18
2005-01-02	2007-04-11	2009-01-13	2011-10-29
2005-01-15	2007-06-27	2009-01-28	2011-11-19
2005-02-08	2007-07-18	2009-02-14	2011-11-29
2005-05-06	2007-12-16	2009-02-26	2011-12-27
2005-06-03	2007-12-30	2009-03-19	2012-01-05
2005-11-23	2008-02-07	2009-04-14	2012-01-23
2006-01-15	2008-02-25	2009-05-31	2012-02-14
2006-01-30	2008-03-08	2009-12-16	...
2006-03-07	2008-03-29	2010-01-09	...
2006-04-02	2008-05-03	2010-05-23	...

Note. — Dates are for beginning of night in format YYYY-MM-DD; UT dates are one day later.

Table 2. Mass-Loss Events for Lo 4

UT Date	HJD–2400000
1992 Jan 28 ^a	48649.70
2006 Jan 16	53751.66
2006 Nov 30	54069.79
2008 Nov 30	54800.78
2011 Oct 30	55864.84

^aWerner et al. 1992